INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012
Dubrovnik - Croatia, May 21 - 24, 2012.

DESIGN FOR HUMAN – VIRTUAL ENGINEERING IS A MEDIA FOR KNOWLEDGE TRANSFER

S. -P. Leino and A. Pulkkinen

Keywords: human, knowledge transformation, virtual engineering

1. Introduction

Communication and knowledge sharing among many product lifecycle stages and stakeholders of value networks should be improved. Data and knowledge should be shared downstream of lifecycle for all who needs it in a right format. Moreover, upstream lifecycle feedback from production, operation and maintenance should be captured and utilized for instance in product development phase as well. This is particularly important in case of human-machine system design. Nevertheless, communication and knowledge sharing are lacking proper means and methods. Based on the findings of literature review and company interviews [Leino and Riitahuhta 2012] it was proposed that in future work a framework model should be built as a basis for developing practical solutions to cover following gaps between current state and desired situation: There is an urge for more practical and adapted implementations of human centred design methods for a specific context in companies, integration of virtual engineering to product processes should be better defined, information models and data transfer between virtual engineering solutions and data management systems need improvement, knowledge management challenges are related to methods, tools and infrastructure for knowledge capturing, transferring and sharing. Hypothesis is that virtual engineering (e.g. virtual reality, virtual prototyping) and other novel tools (like social media) as part of product lifecycle management (PLM) could be medium for enabling better communication and knowledge sharing. Nevertheless, efficient utilization of such means requires development of procedures, processes and information models of PLM. In this paper a framework model to support of closing above mentioned gaps is proposed. Enabling elements for implementation of the proposed model were defined as well.

1.1 Objective and research question

Main objective of our research is to create support for better design of human-machine systems. One sub-goal is to better understand and utilize human (users and other product lifecycle stakeholders) needs and requirements. Another sub-goal is to improve utilization of 3D product data within product processes and lifecycle support. Based on the objectives, research question was formulated as: How bidirectional product lifecycle communication, collaboration and knowledge sharing can be enhanced?

1.2 Structure of the paper

The approach of this paper is multi-disciplinary, combining areas of product lifecycle management, virtual engineering, human factors engineering and knowledge management. At first, technical and methodological background of the study are introduced for a reader. Next, the case study based research approach is more detailed. Observations of case studies are extracted and formulated as results of the study. Results include three levels: a) general PLM framework model, b) enabling embodiments of the PLM model, c) utilization of the model. Finally, the results are discussed and concluded from practical and theoretical implication viewpoint.

2. Technical and methodological background

The main technical and methodological background are introduced in the following sections

2.1 Product lifecycle management

Product Lifecycle Management (PLM) is a business approach which integrates organizations, processes, methods, models, IT tools and product related information and communication, see e.g. [Ameri and Dutta 2005]. PLM has been recognized as one of the key technological and organizational approaches and enablers for the effective management of product development and product creation processes [Abramovici 2007]. Knowledge management is one of the main research issues in PLM field [Ameri and Dutta 2005]. There is also a lot of business potential which can be reached by implementing PLM landscape more widely beyond product design phase. This requires defining needed processes, practices, information models, system architectures and integrations [Abramovici 2007]. Further PLM development targets are discussed in [Leino and Riitahuhta 2012].
There are number of computer aided tools and methods developed in order to streamline product processes and value network collaboration as part of PLM. They can be named in many ways, for instance virtual engineering, virtual prototyping, simulation based engineering, etc.

2.2 Virtual engineering

The terminology of relatively new Virtual Engineering discipline is not yet stabilized. Virtual Engineering includes for instance tools like Virtual Reality, as well as methods and processes like Virtual Prototyping. In this paper Virtual Engineering is a higher level framework where virtual prototyping and virtual reality solutions (Figure 1) belong to.
There are many definitions for virtual prototype. Wang has proposed a reasonable definition and components for virtual prototyping terminology [Wang 2002]: "Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analyzed, and tested from concerned product life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping." A virtual prototype must support the same functions and even more as a physical prototype, i.e. to prove design concepts, evaluate design alternatives or test product manufacturability [Wang 2002]. VR technology combines multiple human–computer interfaces to provide various sensations (visual, haptic, auditory, etc.), which give the user a sense of presence in the virtual world [Seth et al. 2011].

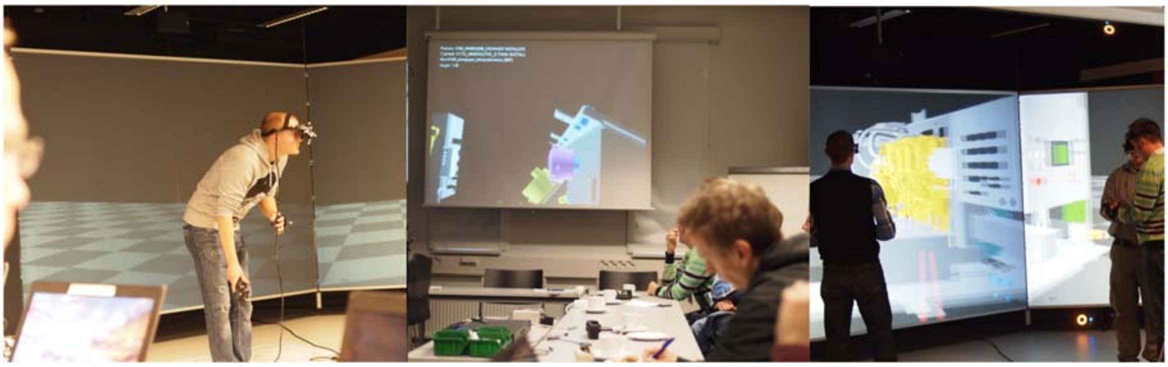

Figure 1. Virtual reality application in a new product review

2.3 Human factors engineering – design for human

Human beings are usually part of a socio-technical system. They are for instance operators of a machine, or participants of a production or maintenance process. Human Factors (HF) requirements along a product lifecycle should be therefore well known in a product development process. There is for example a multi-disciplinary HF approach called "User Centred Design (UCD)" intended to take end-users' requirements well into account, see e.g. [Vredenburg et al. 2002]. Good practices for UCD are described in several standards, e.g. ISO 13407 and ISO TR 18529. Nevertheless, there is often lack of such knowledge among product developers and engineering designers [Leino and Riitahuhta 2012].

2.4 Knowledge management

Knowledge is evaluated and organized information that can be used purposefully in a problem solving process, however systematic management of the organizational knowledge is a demanding task [Ameri and Dutta 2005]. Nonaka [1994] proposed a paradigm for managing the dynamic aspects of organizational knowledge creating processes. Its central theme is that organizational knowledge is created through a continuous dialogue between tacit and explicit knowledge. Nonaka's theory includes four different "modes" of knowledge conversion. The theory of knowledge conversion is also supported by work of [Ameri and Dutta 2005]. They see that the four conversion modes can be described from PLM point of view as follows:

1. *Socialization* – from tacit knowledge to tacit knowledge: The sharing of tacit knowledge between individuals., e.g. web meeting applications, collaboration and visualization tools
2. *Combination* – from explicit knowledge to explicit knowledge: Combining two or more pieces of knowledge to generate new explicit knowledge e.g. expert system which classifies components based on their similarity in geometry.
3. *Externalization* – from tacit knowledge to explicit knowledge: Tacit knowledge is made explicit, e.g. information authoring tools (like CAD systems) and text editors
4. *Internalization* – from explicit knowledge to tacit knowledge: Transforming explicit knowledge into tacit knowledge through learning e.g. search engines, document management, change manaement and work flow management

3. Methods and material

3.1 Research approach

This paper is part of a larger research programme, where first the gaps between current state and desired situation where identified and described (see the Intoduction section). This paper aims to formulate a general prescriptive PLM framework model which collects requirements and concepts for filling the mentioned gaps.
Research approach is multi-disciplinary, combining areas of product lifecycle management, virtual engineering, human factors engineering and knowledge management. Methodologically the approach is based on a) descriptive analysis of industrial case study observations, and b) iterative construction of descriptive model within the cases. This approach aims to generalize practical cases as a concept model. Elements of the model will be detailed in the future publications. Furthermore, practical implications of the model and reference to theory are discussed in this paper.

3.2 Case studies and context

The case studies were conducted in several Finnish national research projects, and in a large EU-project ManuVAR (see www.manuvar.eu) during six years. The research and results of these projects were reported in several publications, see e.g. [Leino et al. 2010], [Krassi et al. 2010].
In these research projects goal was to develop support for designing better human-machines systems accounting integrated needs of business and product lifecycle stakeholders. In particular, manual assembly and maintenance work as well as operation of mechatronic machines were in focus of the studies. Another specific goal was to improve utilization of 3D data among product processes and lifecycle support. The case studies were carried out in co-operation with eight large companies from manufacturing industry sector. Business models of the companies typify configure to order and engineer to order concepts, and products represent largely heavy machinery.

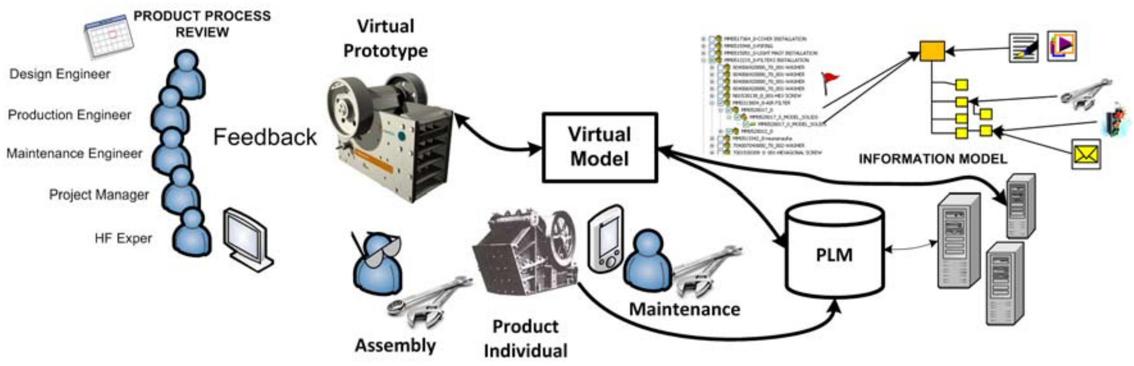

Figure 2. Example of VE based knowledge management

Figure 2 presents a example of one particular case model, which was built to describe a concept called virtual product review. In the review, involved people of a review board are from several organisational groups and product lifecycle phases, namely product design, productization (preparation for serial production), production, service and maintenance, marketing, product management, occupational health and safety, and project management. Involved individuals are designers, production planners, assembly and service workers, etc. They have very different background, knowledge, skills and ability to understand drawings and other more or less abstract product data. Three specific aspects were emphasized within this case: 1) Fetching needed product data from PDM in order to build a virtual prototype, 2) pushing virtual product review feedback and engineering change requests back into PDM, and 3) building PDM data model to support aforementioned aspects. It is remarkable, that in this case PLM architecture includes IT-solutions (Virtual Environment and PDM) from different software vendors. Furthermore, concepts for virtual models utilization in product support (assembly and maintenance instruction, manuals) were created.

4. Results

Results of this paper consist of three sections. Firstly, analysis outcome of case study observations were categorized as general elements of the proposed PLM framework model. Secondly, enabling embodiments as instances of the PLM model were described. Lastly utilization of the model in knowledge transfer was explained. The relationship between the PLM model and enabling embodiments are illustrated in the Figure 3.

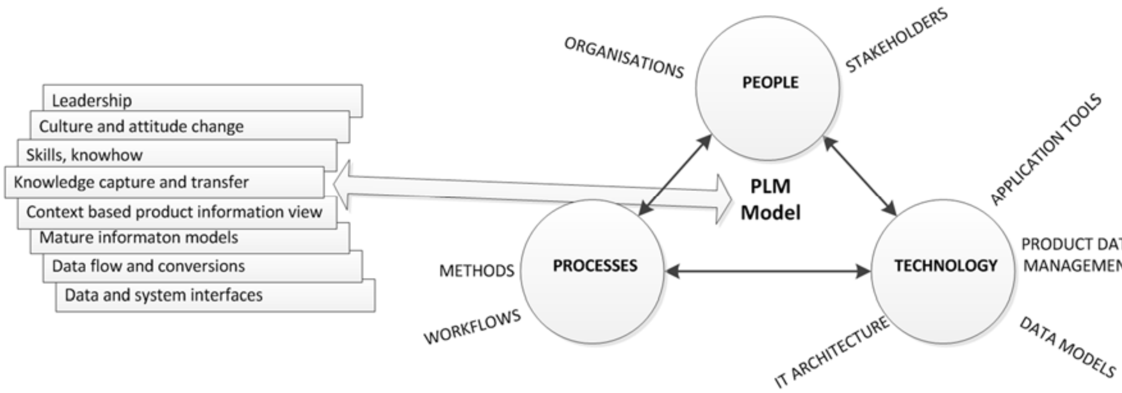

Figure 3. Relationship between PLM Model and enabling embodiments

4.1 PLM model

Fundamental idea of the PLM model is to utilize virtual engineering (e.g. virtual reality and virtual prototyping), and PLM as medium for product lifecycle knowledge communication and knowledge transfer (tacit and explicit). Virtual engineering offers means for on-line, instant communication when PLM enables off-line global knowledge sharing among the whole value network.

PLM processes define what and when will be done by whom. A process has also pre-defined inputs and outputs, e.g. 3D data and analysis result documents. An example of related PLM process definition is reported in [Leino et al. 2010]. A method explains how process transactions will be conducted and supported by suitable tools and applications. A process for instance defines when (what point of a product process) a virtual product review will be set up by whom, and who are the participants of the review. A method related to virtual product review explains for instance how a certain product review will be executed. In the case studies, methods include e.g. product assembly and maintainability design review.

People and processes are essential elements of a PLM framework, but they need to be supported by sufficient IT infrastructure and application tools, i.e. technology elements. Product Data Management (PDM) is backbone of the PLM taking care of product items, structure, and document management. There are countless number of different PLM architectures to fulfil needed processes and transactions as for instance workflows and change management processes. Anyway in order to manage the PLM processes succesfully, adequate data (information) models are needed besides the IT infrastructure. Meaning of product data should be underscored as well. In this paper product data are defined to include all product life related data and information, such as 3D-models, drawings, requirement specifications, virtual engineering simulation models, feedback documents, etc. Metadata model is needed to define structures, classifications, versions and revisions, and processes.

4.2 Enabling embodiments of the PLM model

Above mentioned general PLM framework elements require more specific *enabling embodiments* in case of virtual engineering based knowledge transfer. It is essential that virtual engineering is seamlessly integrated into a company business. This means definition of virtual engineering processes including procedures and methods as part of product and business processes. Implementing such processes require also leadership, educating people and their skills and knowledge through a culture change. A different mindset is needed for efficient exploitation of virtual engineering and peoples knowledge concerning the whole product lifecycle. For example, designers should allow assessment of their unfinished drafts as early as possible.

The methods require know-how, skills and understanding about how to use virtual engineering tools and methods (e.g. virtual reality, virtual prototyping), how to build virtual environment models and simulators, how to run a virtual review meeting session, how to apply the UCD and participatory design methodologies, and how to capture, transfer and save tacit and explicit knowledge for the wide usage during a product lifecycle.

Virtual engineering tools and virtual prototyping may offer medium for communicating and tranfering tacit and explicit knowledge between e.g. workers and designers in real-time. Anyway, the knowledge should be captured and saved in certain data format digitally in order to be usable in a PLM system during the product development and lifecycle. Saving and managing such knowledge in a PLM system requires mature and rich data model. Management of virtual engineering models, hierarchical task models, as well as management of different product structures for product design and development, for production and service require capability to manage parallel product structures and configurations. On the other hand, efficient exploitation of product data during lifecycle require clever data access management and presentation of the product data, i.e. different views to it. Virtual engineering can also act as natural presentation of more abstract data.

PLM IT architecture requires good data and systems interfaces. Some monolithic PLM systems may allow operating around a common database in theory, but usually several systems and data formats are needed from several system vendors, and used in extended enterprises. Actually root cause for many communication and knowledge sharing defects is poor non-integrated and overlapping IT architecture and poor PLM implementation strategy without understanding of real PLM drivers. IT systems are created around functional organisations without compatible information models. Virtual Engineering initiatives are typical examples of inadequate PLM process implementations. Therefore for instance interfaces and procedures for data conversation from CAD to VE and onward back to PDM, as well as integrations in order to transfer metadata between systems are needed.

4.3 Use of the model – knowledge transfer

Figure 4 is intended to give an example of how diverse types of data, information and knowledge as well as medium for transferring and capturing them could be categorized on continuum between abstract – exact, and tacit – explicit product data. The figure emphasizes the role and potential of Virtual Reality as a node point and medium in the transformation process. It is remarkable that all product lifecycle data and information are perceived as product data – tacit and abstract knowledge as well.

The properties of a technical system are called requirements. Requirements specification is issued from the view point of a customer or user, and is transformed by the designer into a design specification to guide the design. This transformation from custormer or user requirements is critical, but often very difficult because they are often abstract and include tacit knowledge. Virtual engineering is claimed to enable this transformation better by offering a medium for visualising and communicating abstractions and tacit knowledge. This transformation covers mainly the "socialization", "externalization" and "internalization" of [Nonaka 1994] paradigm. It is important to mind that exact information for a design engineer (e.g. a new product concept) might be abstract for a worker. Respectively, workers hold tacit knowledge about manual work which a designer could capture only in virtual workshop acting with with physically non-existing virtual prototype of a product concept.

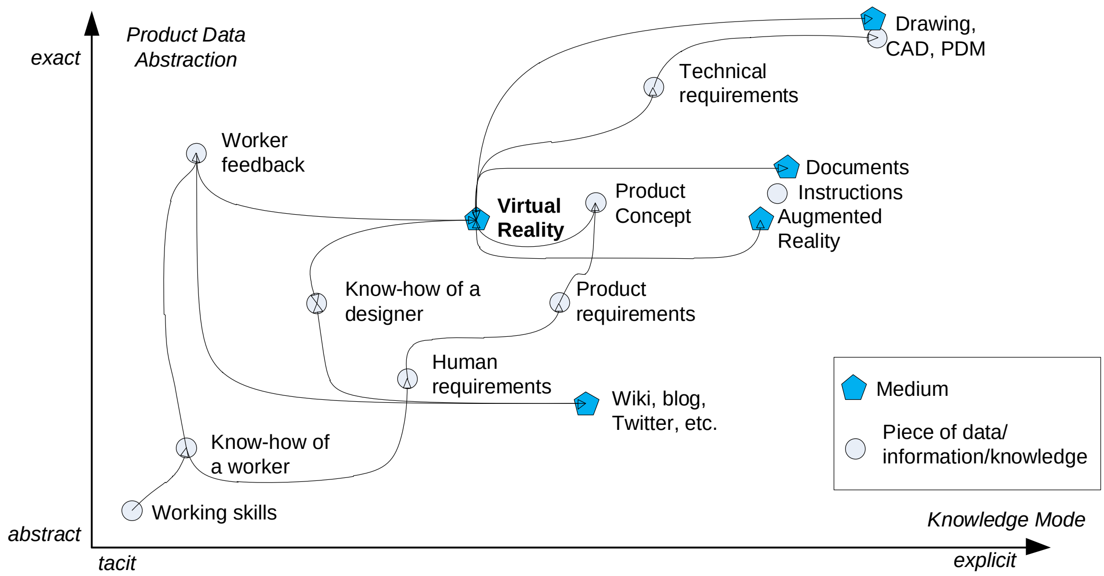

Figure 4. Instance of VE based knowledge transfer model

5. Discussion

Aim of the research is to create support for better design of human-machine systems. One sub-goal of the research is to better understand and utilize human (users and other product lifecycle stakeholders) needs and requirements. Another sub-goal is to improve utilization of 3D product data within product processes and lifecycle support. Based on the objectives, research question was formulated as: How bidirectional product lifecycle communication, collaboration and knowledge sharing can be enhanced? This paper answer the research question in two ways – by what means, and in which manner knowledge can be transferred within human-machine system design and product life support. In other words, a) general elements of the PLM model were defined, b) enabling embodiments and instances of the elements were explained, and c) application of the model in transformation between tacit and explicit, as well as between abstract and exact product data was reported. Knowledge transformation and transfer enable understanding human needs and communication between designers and stakeholders. The model is also built on top of efficient utilization of 3D product data.

This paper addresses practical implications and notions for industry. It emphasizes potential of tacit knowledge of workers and other product lifecycle stakeholders. This is meaningful for business, because it enables designing better products, and more efficient production and service systems. The created PLM model proposes how knowledge could be captured and transferred using virtual engineering, human factors methods, and IT-systems. Existing and reported PLM models are usually thin (focused to items and drawings) and/or high level without real reference to practice [Leino et al. 2012]. Novelty of this paper is manifested by holistic, but practical approach. Though it is not possible to deliver highly detailed descriptions because of space limitation. In order to give a more solid references to practice of industry, links to engineering change management and requirements management processes are given: Change management is a particular process which could be improved by virtual engineering. Firstly, virtual engineering enables change management when physical products do not exist. Another significant benefit of virtual engineering is gained by better communication and collaboration between stakeholders of a product life and supply chains. Product data of different abstraction levels can be visualized in order to better clarify its meaning. Especially immersive virtual environments offer media for natural communication, and tacit knowledge transfer between people with different skills and backgrounds. For instance assembly workers can assess a design change by walking around a virtual product, or designers can assemble products similar way to real product. The concept of closed loop PLM can be implemented by gathering knowledge feedback from production, logistics, commissioning, maintenance, operations, etc. via virtual engineering. Instead of sub-optimization, virtual engineering facilitates comprehensive view on change consequences considering the whole product lifecycle and supply chain leading to total optimization. More detailed benefits of virtual engineering in change management process can be realized in form of: a) populating and communicating change requests, b) evaluation, validation and agreement of change requests virtually, c) communicating the upcoming and realized changes. Product changes are related to (customer/user) requirements specifications, design specifications, supply specifications, etc. Transformation of requirements can be communicated via virtual engineering in order to avoid misunderstandings. Requirements are often context dependent, meaning e.g. conditions and capabilities of production system or operations, including human actors. Virtual engineering enable better context understanding as well. Virtual engineering enables efficient design review processes, including customer requirements validation, customer/partner engaging, and other stakeholder viewpoints as well.

Validity of the results are currently restricted to the case studies, and is based on discussions between researchers and representatives of the companies. It is proposed that the model could be beneficial wider in industry with similar type of business models. In future, as part of the larger research programme aim is to develop the model towards generalization and reference to design science theories. At this stage of the research "Theory of Technical Systems - TTS" of [Hubka and Eder 1988] is considered as a frame of reference which offers concepts for explaining the meaning of the PLM model elements. This is a way to establish connections between the multi-disciplinary areas of product lifecycle management, virtual engineering, human factors, knowledge management, and engineering design. For instance, TTS defines concepts of system "property" and system "structure". Term "property" may cause some difficulty for a engineer, because it includes also operational properties like manuracturability, transportability, maintainability, operability, lifecycle costs and many others [Hubka and Eder 1988]. These properties can be also considered as issues of product lifecycle states. Design engineers should assess the proposed system through all of these states, in order to examine how suitable the system is likely to be for the requirements in each state, but experiments or tests on models can assist in cases when the imagination is inadequate [Hubka and Eder 1988]. On the other hand, suitability of the system is also a subjective property. It depends on viewpoint of the assessing person. Virtual engineering and virtual prototyping are perfect means for examining the suitability of a designed system in very early phase of product process involving also the real end users, before physical products are built. This VE based transfer process should be seen as means for closing the knowledge loop of product lifecycle already in virtual design phase of product process. The behaviour of any technical system is closely related to its structure [Hubka and Eder 1988]. The structure is not only important for the function (mode of action) of the technical system, but also for the principle of managing the process of building and manufacturing the system (mode of construction). This mode of construction can be analysed simultaneously with mode of action using virtual engineering.

6. Conclusion

Aim of our research is to develop support for better human-machine system design. The fundamental idea of th support is based on virtual engineering based knowledge transfer within a product life, between designers and other stakeholders. This paper proposes a holistic practical framework model which describes needed elements to conduct the knowledge transfer, i.e. PLM model and enabling embodiments of the model. Examples of the model usage are described in the paper as well. The practical model is based on case studies, therefore it's validity is restricted to similar type of settings. In future, goal is to generalize the model and establish a link to design theory. Elements of the model and industrial benefits will be detailed in future as well.

Acknowledgement

Part of the research leading to these results has received funding from the European Commission's Seventh Framework Programme FP7/2007-2013 under grant agreement 211548 "ManuVAR". National Finnish research projects Virvo, Kvalive, Lefa and Fudge, funded by the the Finnish Funding Agency for Technology and Innovation (Tekes), have also contributed to the this research. We would like to express our acknowledgements for all colleagues in those projects. Addiotionally, thanks for Lauri for the review meeting photos.

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Simo-Pekka Leino, M.Sc. (Eng.)
Senior Scientist
VTT Technical Research Centre of Finland, Systems Engineering
Tekniikankatu 1, 33101, Tampere, Finland
Telephone: +358407377184
Telefax: +358207223499
Email: Simo-Pekka.Leino@vtt.fi
URL: http://www.vtt.fi